Development of an Effective Self-Cleaning System to Minimize Fouling in Heat Exchangers

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Abstract

Power plant steam condensers use cooling water for condensation of exhaust steam from turbines. Depending on the concentration of cations in the cooling water, changes in temperature result in the precipitation of insoluble metal salts on the tube walls hence impeding heat transfer, leading to fouling, a threat on the heat transfer efficiency of the condenser. The research was carried out at a power station in Zimbabwe where offline mechanical methods used to clean the tubes were observed to be slow and inefficient, hence increasing downtimes. The use of spherical rubber balls was proposed where they were injected into the cooling water to scrub off dirt on the tube surfaces as well as creating turbulence to prevent the dirt from settling on the tube walls. Ball sizes of diameter less than the tube sizes were preferred in order to cater for possible thermal expansion of the rubber material on exposure to elevated temperatures. A magnetic water treatment unit was added to facilitate the formation of weak precipitates of the metal salts for ease of removal on cleaning. The design and implementation of the research results had the potential of saving the company on downtimes during condenser cleaning.

Keywords
Condenser, fouling, foulant, heat exchanger

1. Introduction

The case study company, a power plant based in Bulawayo, Zimbabwe uses the shell and tube heat exchangers for condensing exhaust steam from the turbines. The cooling water passing at the tube side had a tendency to accumulate deposits on flowing through the tubes. These deposits increased with time and in case of natural water, minerals such as calcium and magnesium tended to form insoluble salt precipitates in the pipe interior wall. This gave rise to fouling, an accumulation of unwanted material on the pipe walls, effectively blocking the smooth functioning of the condensers (Bagheri & Mirbagheri, 2018). Fouling can usually be distinguished from other surface-growth challenges, in that it occurred on the surface of pipe walls of the heat exchanger tubes which were meant to condense the exhaust steam from the turbines but because of the deposits, the function of the heat exchanger was affected. The methods employed by the company to clear the deposits were not only manual and time consuming but were also ineffective in that the entire plant had to be shut down to accommodate the maintenance and cleaning process.

There were increased downtimes leading to loss of electricity generation and supply to the national grid. This situation was worsened by the erratic supplies of electricity due to the perennial power deficits in Southern Africa dating back to the 1990s (Mohammed et al, 2013). Following the global financial crisis of 2008 (Bakrania & Lucas, 2009), Southern African countries were affected to the extent of failing to provide adequate power supplies for the smooth functioning of companies, particularly energy intensive industries. Due to political instability and macroeconomic fundamentals that were not adequately managed, Zimbabwe was one of the worst affected countries. Apart from companies scaling down due to the limited supplies of power, capacity utilization at most industrial establishments declined to its lowest, averaging 10% in 2009 (Gadzikwa, 2013). Those companies that were fortunate not to be liquidated reduced their shifts from by 30%, concentrating on off-peak periods in order to avert the problem of load shedding that the country introduced following the crisis. In addition, Zimbabwe also faced the challenge of importing power from neighboring countries as most of these countries equally faced the same challenges of power supply. Although the Southern African Power Pool, which was established in 1995 by the Southern African Development Community (SADC) member states as a cooperation of national electricity companies for electricity trading among the countries, was well capitalized, it has not been able to overcome the persistent power deficits in the region due to a number of reasons such as the effects of the financial crisis, absence of dependable sources of power supplies and insufficient generation capacity to meet the ever growing demand (Miketa & Merven, 2013).

The SADC member states also lacked the skills for developing alternatives sources of energy due to the migration of professional engineers in search of better opportunities abroad (SAPP, 2009). Such power pools could only be sustained in regions with developed grid interconnections, good generating capacities and a legal framework to enable the smooth functioning and trading of electricity (Niyimbona, 2005). According to Southern African News Features, 2017, some of the mainland SADC countries such as Angola, Malawi and Tanzania were not at all connected to the SAPP regional grid to contribute to sustainable energy for all. This greatly reduced the number of countries that could trade surplus electricity to those like Zimbabwe which were heavily affected. As such, the small amount of power generated in the country was vital and so was the effectiveness of the equipment used in such generations. The aim for this research was to maximize the operations of the power station through the development of an effective cleaning system which continuously cleaned the condenser tubes of the heat exchanger without necessarily powering down the power station. This was accomplished through the analysis, optimization and selection of the most suitable and effective technique for the cleaning the condenser, further development and design of the selected system as well as verification of the effectiveness of the developed system. This was ultimately meant to address the power deficits, albeit in a small way, through the increased rate of generation, reduced operational costs required for the cleaning process, improving the efficiency of the heat exchanger.

2. Background and Literature Review

The performance of power plant equipment is dependent on a number of factors, chief among them the cleanliness and free from debris as much as possible. The presence of unwanted deposits especially on the pipe walls affect the efficiency of the operations of heat exchangers, hence the vital need to ensure that they are kept free of such debris in order to maintain efficiency or surpass it for uninterrupted operations (Ibrahim, 2012). In that regard, it is equally essential to detect any buildup of such deposits at an early stage to enable clearing them before they accumulate to the extent of shutting down the plant (Pham et al, 2017). The routine maintenance and cleaning of the shell side of heat exchangers is essential to avoid clogging which can affect the performance of the entire plant. The problems encountered in maintaining cleanliness of heat exchangers largely depend on what the heat exchangers are used for. In some cases, some of the functions result in sticky layers of polymers and in other cases such as the case study power plant, solid deposits were created which required specialized cleaning in order to adequately remove the debris. Although in many of the cases, heat exchangers can simply be cleaned by high pressure water jets, these do not adequately clear all the debris and with time accumulations adversely affect the performance of the heat exchanger. In addition, the use of high pressure water jets may loosen the debris from the shell sides but when it is either done incorrectly or completely, the loosed debris will simply be forced further down into the tube bundles, further impeding the operation of the heat exchanger or even damage the equipment or open up new surfaces for other deposits to accumulate, hence reducing the time between maintenance routines. The traditional routine for the maintenance and cleaning of the external shell sides of heat exchangers is a two-stage process that needs to be done correctly in order to realize the full value of the equipment (Georgiadis et al, 1999). Apart from detecting an accumulation of debris, it is also essential to visually inspect tube bundles and shell sides prior to and after cleaning to ascertain the complete removal of such deposits.

The inspection and detection helps in facilitating the clearance of pathways to ensure that all debris are removed and flushed completely apart from inspecting and checking for any possible damages to the intricate parts of the equipment (Pham et al, 2017). In the event of restrictions to accessing the tube bundles and internal parts of the heat exchanger, appropriate camera equipment can be improvised to ensure that cleaning of the debris would have been done properly. Several techniques for cleaning heat exchangers have been devised by many companies over the years. Such companies include Tube Tech and NLB Corporation which specialize in using the ShellJeTT technology for cleaning the external shell sides of heat exchangers (NLB, 2016). This technique utilizes the high pressure water jet technology for cleaning any surfaces. Other unique cleaning techniques offered by these companies also include BladeSpec inspection system that provides precision cameras to enable visualization of areas cleaned or to be cleaned. Such systems have been popularized by their ability to enhance productivity and uninterrupted operations of heat exchangers against the traditional manual water-blasting while reducing the exposure of the operators to debris and high pressure jets. Through the use of remote and wireless controls, they also allow the operators to stay clear of the area under maintenance. Figure 1 show a snapshot of typical debris that accumulate on the external side of heat exchangers.

Figure 1. Snapshot of Debris on Pipe Walls of Heat Exchangers

Heat exchangers find wide applications in industry, ranging from refineries, chemical processing, heating, refrigeration, air conditioning and power plants such as in this case study. Fouling, as shown in the snapshot in Figure 1 leads to oversized heat exchangers which may result in losses in energy generated or transmitted (Sadouk, 2009). The effects of such accumulations affects the operations of heat exchangers in different ways such as development of pathogens and health risks in food processing and contamination (Haeghebaert et al, 2002) as well as the loss of generation of power due to downtimes, in the case of power plants (Cheng et al, 2018). The operations of heat exchangers are controlled by heat and mass transfer equations in the form of partial differential equations ((Incropera et al., 2011) but generally difficult to use because of representative state vectors which belong a space function such as the state vector which is of infinite dimension. Hence, researchers ended up approximating through finite dimensional models in order to detect fouling on the external sides of heat exchangers.

All such methods and models, especially those employed by Tube Tech and NBL Corporation were effective ways of detecting and cleaning off debris on pipe walls of heat exchangers. However, these are methods and equipment used are all capital intensive. Considering the economic situation in Zimbabwe following the financial crisis of 2008, other innovative and affordable ways to achieve the same purposes were required. This research therefore focused on the case study power plant company to establish the challenges encountered in the accumulation of debris and the cleaning thereof through site visits, data collection and literature search in order to develop an affordable and effective heat exchanger cleaning system to minimize fouling in order to realize continuous and uninterrupted operations of the power station. This was aimed at maintaining and maximizing the output of the power plant to augment power generated for the national grid in any way possible while minimizing the importation of power in view of the limited financial capacities.

3. Research Methodology and Concept Analysis

A number of site visits were made to the power station coupled with observations and data collected as well as literature on available techniques for cleaning such those employed by Tube Tech and NLB Corporation. It was apparent that the dual use of the combination of rubber balls with a magnetic water treatment system was probably the most ideal and affordable under the circumstances and economic situation. The development and design was also aided by the used of Solid Works for analysis and simulation as well AutoCAD for the concept drawings. The principle of the dual use of rubber balls in conjunction with a magnetic water treatment system are shown in the schematic on Figure 2, upon which the development of the cleaning system was based.

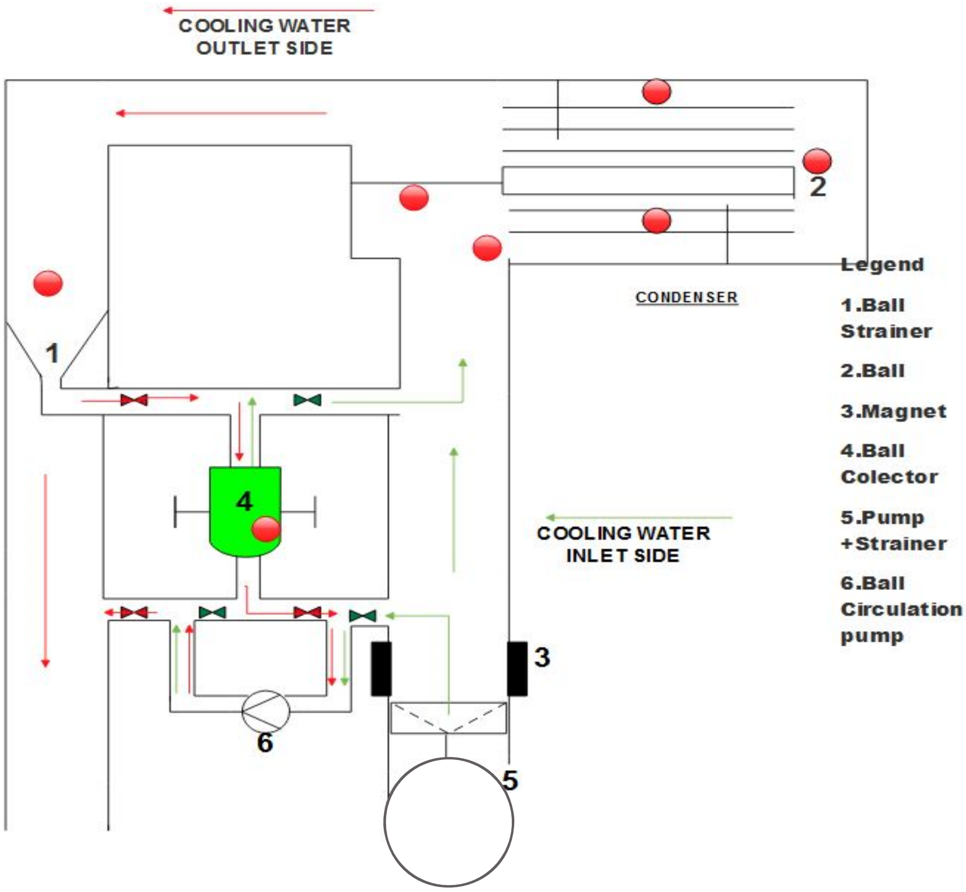


Figure 2. Combined Rubber ball cleaning system with a magnetic water treatment system

The cycle for this concept began initially with rubber balls loaded in the ball collector (4) when the valves are all closed. A Programmable Logical Controller (PLC) was introduced to control system valves to open or close (in green) such that some of the cooling water at the inlet side is bypassed by a small centrifugal pump (6) through to the ball collector (4). The balls in the collector were pushed by the pumped water out of the collector until they flushed into the main cooling water flow towards the condenser inlet head. The magnetic water treatment system (3) uses coils or solenoid that is wrapped along the length of the tube to be treated. A signal generator of changeable frequency was used to provide a current pulse to the coil leading to formation of an electromagnetic field strength around the tube axis. As the water flowed through the field it experienced the Lorenz force such that encaged metal ions of magnesium and calcium were released (Mosin & Ignat, 2014). The consequential field was depended on the flow rate. High and low flow rate would not be conducive for the process. The magnetic field designed were in the range of 3.5 - 136mT and in the case of calcium, it precipitated in a sludge form, commonly referred to as aragonite, which was easy to remove compared to hard calcite. Formation of calcium deposits can be reduced by 70 percent and no hard scales will be observed together with bio fouling slimes (Smith, et al, 2003).

For the magnetic unit design, a copper wire solenoid was used to generate a uniform magnetic field concentrated in the center of the coils hence magnetizing the pipe such that as water was magnetized as it flowed past this portion. The appropriate constraints required to produce the required magnetic flux to de-mineralize the cooling water were determined as follows:

According to Ampere's law; $BL=\mu NI$, where B is Magnetic flux density (136mT) (Morvay & Pálfalvi, 2015; Rajaraman, 2001), L is length of solenoid (1m), N is number of turns (1500), I is the current in the coil in Amps, μ is the absolute permeability, H/m, μs is the relative permeability for steel, H/m, μw is the relative permeability for water, H/m and μo is the relative permeability for air. Therefore:

$\mu = \mu o\ (\mu s + \mu w)$ (water plus cooling water pipes acts as the core)

$= (4\pi \times 10\ \text{-}7)\ (0.999+100) = 0.000127$ H/m

The current required in the coil $I = BL/(\mu N) = (136 \times 10^{-3})(1)/0.000127\text{x}1500 = 0.714$A

The power required for energizing the coil $P = I^2 R$, where the resistance of the solenoid wire,
$R = \rho L/A$ where A and ρ are the area and resistivity of copper solenoid (0.02cm diameter).

$R = (1.7\text{x}10^{-8})\ (1)/\ ((\pi\text{x}0.02\text{x}10^{-2})^2)/4) = 0.54\Omega$

$P = (0.714)^2\ (0.54) = 0.275$ W

Thickness of the coil wire from current density: $J=I/A$, where J is current density (500 A/m^2) for Copper.

A is cross-sectional area for the Copper wire (m^2) = 0.714/500 = 0.001428 m^2

But A is also $(\pi D^2)/4$, implying that the diameter D of copper wire required is 42.64 mm^2

For tube cleaning, as the cooling water and ball mix passes through the condenser tubes due to pressure variance, each ball generates turbulent layers around itself whilst in motion hence aiding the ball to push foulant off the heat transfer surface and disturbing settling of the dirt as shown in Figure 3.

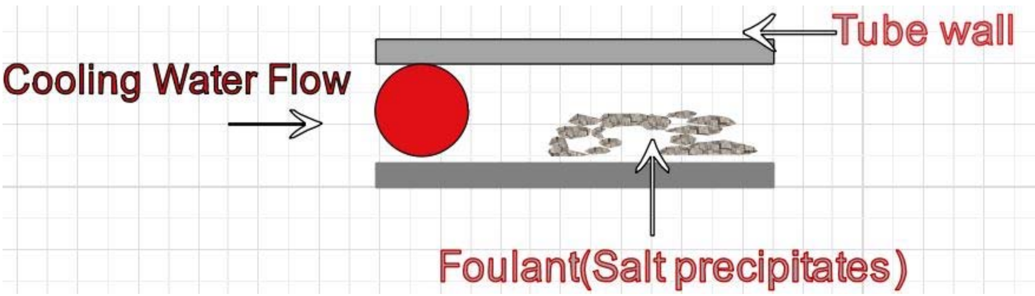


Figure 3. Rubber Ball during foul removal

Rubber balls such as those produced by Taprogge (Kleinebrahm, 2017) were selected based on the factors; nature of foulant was precipitation scaling due to metal salts and brass as the tube material. To allow for better distribution of the balls towards the tube bundles, the specific weight of the ball (Υ_b) was equated to that of water (Υ_w). This ensured density of water (ρ_w) was equal to that of the balls (ρ_b). According to buoyancy the ball would not float nor sink but instead stay within the water body. $\Upsilon = \rho_w\ g = \frac{m_b\ g}{v}$, Assuming $\rho_b = \rho_w$,

The mass of ball: $m_b = \rho_w x\ (\frac{4}{3} x\Pi\ R^3) = 999.8 \text{ x } (4/3) \text{ x } \boldsymbol{\Pi} \text{ x } (0.015)3 = 0.014$ kg

Based on the 2nd law of thermodynamics; conduction heat transfer is observed whenever two bodies of different temperatures are involved so as to attain a uniform temperature gradient. For the determination of how much the ball material was affected by exposure to high temperatures, ball motion was analyzed under the worst case scenario in such a way that the ball formed almost a tight seal to the tube surface. Considering the subsequent thermodynamic setup of heat transmission between Tube (3) and thin water film (2) through to the ball (1) as shown in Figure 4, where Q is heat transfer rate, W, L is length of tube, mm, r is radius of ball, mm, t is temperature, °C and assuming that Q within the system is the same, this implied that:

$$Q = k_1 2\Pi L\,(t_3 - t_2)/ln\,(r_3/r_2), \qquad Q = k_2\, 2\Pi L\,(t_1 - t_2)/ln\,(r_2/r_1)$$

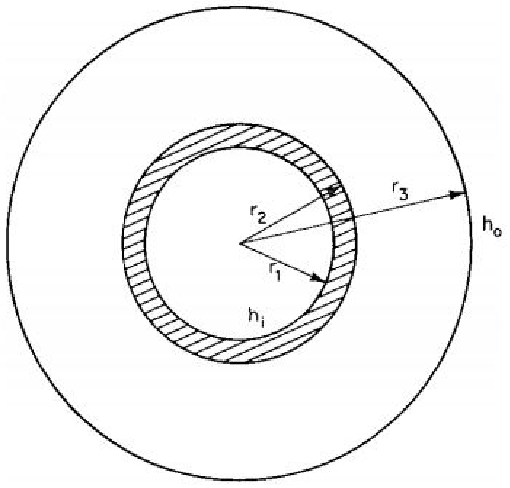


Figure 4. Ball and Tube System under Heat Transfer

Where t_3 is the tube wall temperature from the preliminary calculations. (29.8°C), t_2 is the intermediate temperature on the thin water film in-between ball and tube surface (29°C), also the max temp rise at the tube side, t_1 is the temperature of the ball, k_1 is the coefficient of thermal conductivity for brass tube (104W/m K), k_2 is the coefficient of thermal conductivity for the water film (0.59W/m K), r1 is the ball radius (15mm) (assuming a smaller diameter than tube diameter), r_2 is the tube inner radius (Diameter 16mm), r_3 is the tube outer radius (Outer Diameter 17.6mm) assuming thickness of 10% inner diameter. The heat transfer rate between the layers in the system would be the same:

$$Q = k_1 2\Pi L\,(t_3 - t_2)/ln\,(r_3/r_2) = k_2\, 2\Pi L\,(t_1 - t_2)/ln\,(r_2/r_1)$$

Basing on the above relationship the ball temperature t_1 due to heat transfer can be obtained from:

$$104x2\Pi x\ 14\ x\ (29.8 - 29)/\ ln\,(17.6/16)\ =\ 0.59x2\Pi x\ 14\ x\ (t1 - 29)/ln\,(16/15)$$

$t_1 = 85.3$°C

This was the expected final temperature on the ball when exposed to elevated temperatures. Rubber absorbs heat energy whilst it is a poor emitter hence the obtained temperature was reasonable considering its properties. Increase in temperature in the rubber ball due to its absorbance of heat energy will result in thermal expansion of the rubber ball. Considering that L_1 is initial ball diameter (Diameter will be assumed 15mm thus less the tube diameter), L_2 is final ball diameter after exposure to heat, mm and ά is the coefficient of thermal expansion for rubber. Assuming that when the ball is injected into the cooling water flow it attains the same temperature as that of water (25°C).

ΔT is the temperature difference on the ball = final ball temperature - initial ball temperature = 85.3 – 25 = 60.3°C.

Therefore: $L_2 = L_1 + L_1\,ά\,\Delta T$ = 15 + 15(67 x 10^{-5}) x 60.3 = 15 + 0.60 = 15.60 mm.

Ball linear expansion when exposed to the condenser conditions is 0.60mm. Basing on the above characteristics the high temperature Corundum coated R160 or R130 ball types of diameter 15 mm were selected such that in case of expansion (Diameter) = 15+0.60 =15.60 mm thus advantageous in that the ball and tube form an interference fit hence additional thoroughness in cleaning due to improved contact stability of the ball and tube surface. Selected balls were appropriate for hard metal scales, initial cleaning of new tubes and surface smoothing. In several cases tests were done by manufacturers to determine the amount of balls per cycle as well as frequency of ball injection such that an optimum was reached where at least every tube was cleaned. To avoid cases of missed tubes, an increase in ball numbers from 10% to 30% of the total tube number per pass can also increase the probability of cleaning every tube (Kleinebrahm, 2017). Number of balls per cycle =30% x N_{tp} = 0.3 x (9050/2) = 1 358

Probability that a specific tube is cleaned: Assuming that in a day at most 40 cleaning cycles are done; the scenario above satisfied conditions required to create a binomial model (Crawshaw & Chambers, 1984). Finite number of trials (n) carried out (hence number of cleaning cycles). Trials were independent of each other and the outcome was either success (ball passed through a specific tubes) or failure (ball did not pass through a specific tube). Hence probability of success p was the same for all trials (cycles). Considering a discrete variable X as the number of successful outcomes after n trials, it implied that X~ *(n, p)* such that: $P(X = r) = {}^{n}C^{\,r}\, q^{\,n-r} p^{r}$ where r is the number of successful outcomes.

Case I: Using 10% balls, probability of success p = 0.1 and probability of fail q = 0.9. Based on the model above, we now seek to determine the probability that after 24 hours ball fails to pass through a specific tube, hence r = 0 for n = 40, q = 0.9, p = 0.1 and P(X=0) = 0.0148

Case II: Using 30% balls, probability of success p = 0.3, probability of failure q = 0.7. Based on the same model above, we also seek to determine the probability that after 24 hours ball fails to pass through a specific tube, hence r = 0 for n = 40, q = 0.7, p = 0.3 and P(X=0) = 0.000000636

By Comparison; this implied that the probability was high for a tube to be adequately cleaned after 40 cycles when the ball charge size was increased to 30%. On exiting the condenser at the cooling water outlet side the balls are trapped by the perforated strainer (1) as shown in Figure 5 to prevent them from going downstream. Water passes through the perforations as balls are trapped.

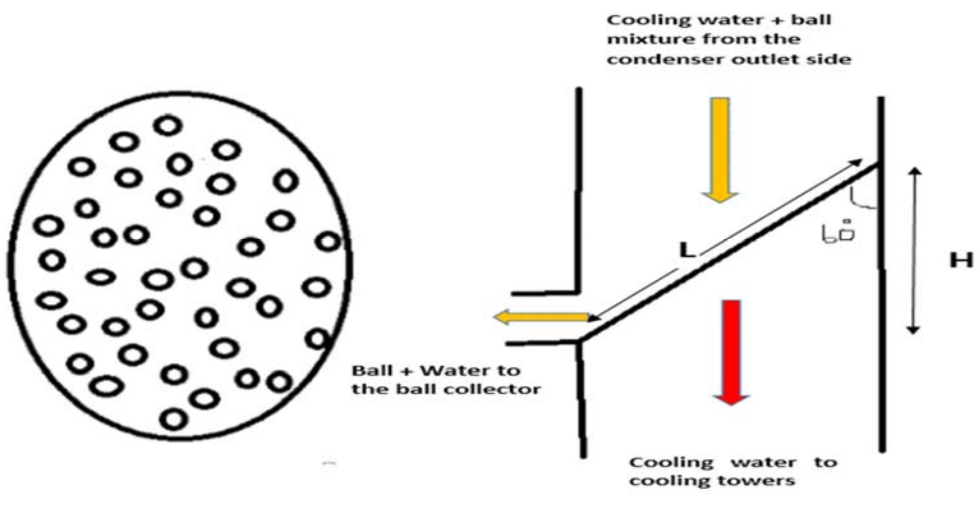


Figure 5. Strainer orientation at the cooling water outlet side

Following the red arrows on Figure 2, the PLC was programmed to open the red valves at the same time as the green ones were closed. The pump then began to draw water from the strainer (1) together with the balls back into collector (4). Balls were trapped in the collector and prevented from passing through by the strainer while water passed through the collector back to the main cooling water outlet flow until the cycle ended.

Power needed when diameter is 3times ball size (DN48.3mm)
Centrifugal pump characteristics operating-point is at 31m Head at a flow rate of 12.5m3/hr. (0.0035m3/s), Type: Series e-90, Impeller Diameter: 5.25 inch, Pump Efficiency - 59%, Speed - 3450RPM (1AAB), Motor Power: 3HP, Net pressure suction head NPSHR = 5m
Therefore, Power to the Pump Shaft: $P = \frac{\rho g Q H}{\eta} = \frac{(1000x9.81x0.0035x31)}{0.59} = 1.80kW$

Power needed when diameter is 2times ball size (DN33mm)
Centrifugal Pump Characteristics, Operating Point is at 32m Head at a flow rate of 5m3/hr, (0.0014m3/s)
Type: Series e-90, Impeller Diameter: 5.25 inch (133.4mm), Pump Efficiency: 42%, Speed: 3450RPM (1AAB), Motor Power: 3HP
Therefore, Power to the Pump Shaft: $P = \frac{\rho g Q H}{\eta} = \frac{(1000x9.81x0.0014x32)}{0.42} = 1.05kW$
The second consideration in which the tube size is twice the ball size requires less energy hence it is cost effective and has even a better probability of being cleaned effectively.

4. Results and Design Analysis

4.1 Strainer

The strainer acted acts as the ball collector to prevent the balls from passing through and maintaining them in the circulatory loop. Due to the cooling water passing through the strainer, it impacted the strainer whilst in operation. In case of failure on the strainer it meant no balls were collected hence no ball circulation was achieved. This meant that the system would not save for its intended purpose. An analysis was carried out to determine Von Mises Stress on the strainer open area. In this analysis only a small fraction of the perforated area (25mm x25mm x 15mm) was considered on the strainer. Using the known pressure within the pipe flow in the main cooling water tube (50 psi), force expected on a unit area under analysis was obtained as (219N). The overall analysis carried out using Solid Works showed that Von Mises stress expected on the strainer plate was 1.9 x 10^6 Nmm^{-2}, thus less than the yield strength of the perforated material of 3.650 x 10^7 Nmm^{-2} as illustrated in Figure 6.

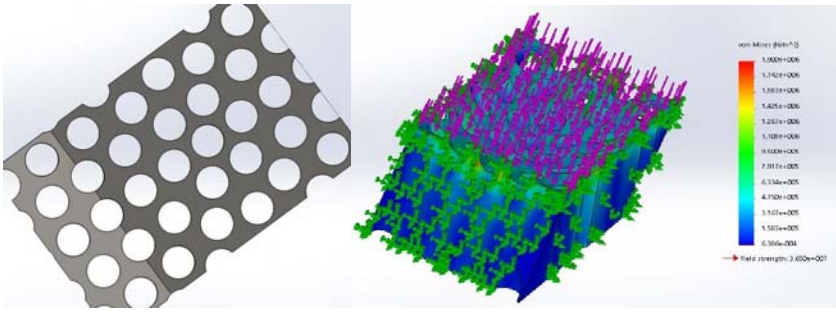


Figure 6. Von Mises Analysis on a Perforated Strainer Segment

4.2 Condenser Tube

The rubber balls in circulation were coated with abrasive materials. In cases of no foulant in the tube or if the ball moved towards tube walls, it implied that it directly contacted tube walls along the flow. The effect of the ball contact on the tube had to be verified if it was sufficient to abrase the accumulated deposits on the walls without damaging the condenser tubes. In this analysis the thrust force on the ball was obtained from ball motion analysis which was considered to be the same force experienced on the tube along its wall. The resultant Von Mises stress after the finite element analysis in Solid Works as shown in the collage of the resulting models in Figure 7 was found as 2.002 x 10^6 Nmm^{-2}, hence less than the yield strength of the brass tube material, i.e. 2.397 x $10^8 Nmm^{-2}$. Both designs were safe because the attained Von Mises stress of the models was lower than the corresponding yield strength in both cases.

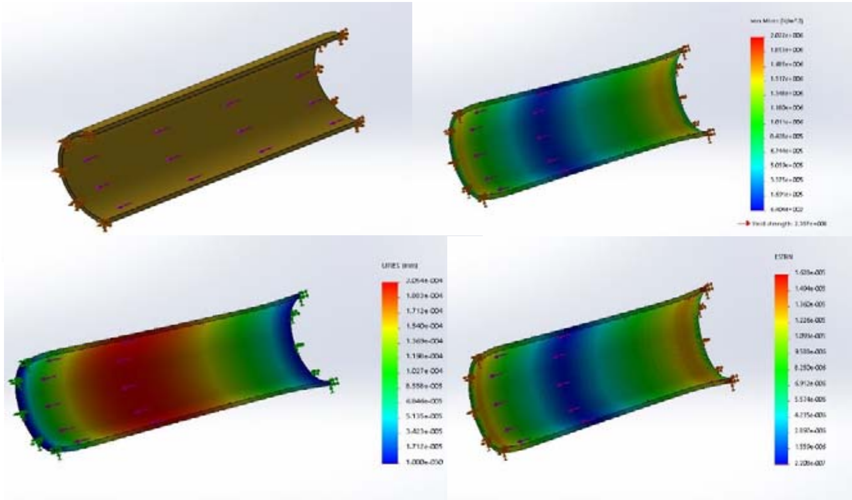
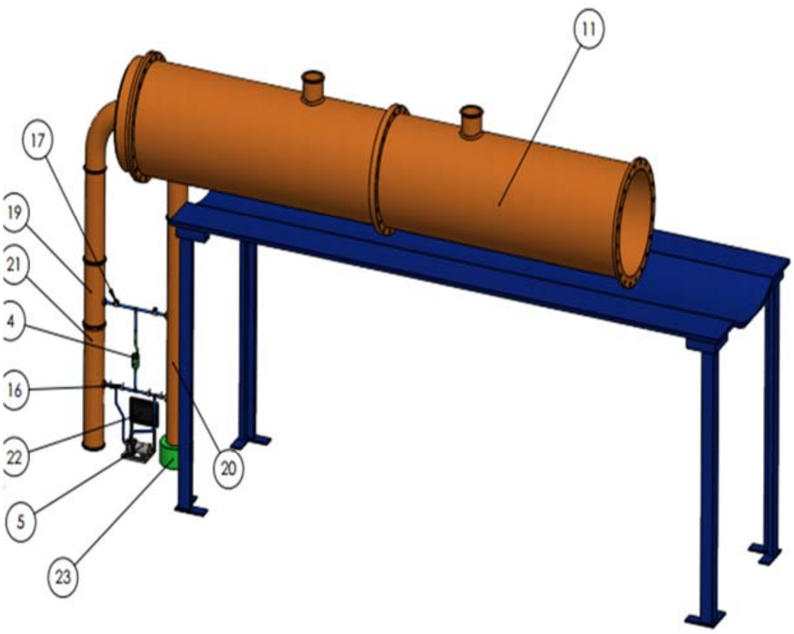


Figure 7. Von Mises Stress on the Condenser Tube



4	Ball Collector vessel	1
5	pump-centrifugal-1	1
11	Turbine Condenser	1
16	Control Valve	4
17	Check Valve	2
18	motor base	1
19	Ball Collecter Site	1
22	PLC for valves and Magnetic unit control	1
23	Magnetic Water Treatment Unit	1
20	Cooling Water Inlet pipe	1
21	Cooling Water Outlet pipe	1

Figure 8. Model of the Cleaning System Developed using Solid Works

4.3 Economic Analysis

The cost of manual cleaning depended on the contracted company but after consulting and data collected at the power station, a reasonable average was found to be \$4,500 per condenser.

This amount was equivalent to the yearly saving that can be done on the condenser unit if maintained clean throughout its operations. From the bill of quantities in Figure 8 and estimations of the costs the various parts listed, the total cost for manufacturing the unit was estimated at \$5,283 giving a payback period of

Payback period = (investment cost) / (Average yearly savings) =1.174 (1 year and 2 months).

5. Discussion and Recommendations

Based on the data collected at the power station and considering the startup and shutdown of the processes during the cleaning period, the cleaning process usually stretched for a period of 6 working days. Hence the total time lost due to cleaning was 144 hours. The average energy generated by the power station was 30 MW which implied that a total of 4,320 MWhrs were lost during the 6 day maintenance period. Considering that the Zimbabwe Electricity Supply Authority tariffs are currently pegged at 11c per KWh, the total cost due to downtime and maintenance was $475,200 (4,320 x 10^3 kWhr X 0.11c per kWhr), an amount that can be saved by employing the proposed cleaning system, less the investment cost of $5,283. Further improvements in the proposed system may be necessary in terms of reducing ball losses, improving ball distribution on tubes, development of more robust balls resistant to wear as well as controlling and monitoring of motion in the tubes to ensure that all tubes are cleaned when they are supposed to. A Hazard and Operability Analysis (HAZOP) was also carried out to ensure the identification and eradication of hazards associated with the developed cleaning system. Potential hazards that may arise due deviation of the design from its expected operational conditions are noted and are listed in Table 1.

Table 1. HAZOP Analysis for the Ball Cleaning System

Deviation	Causes	Consequences	Recommendation
No ball flow to the condenser	Recirculation pump malfunction	Increased fouling rate noted by decreased flow rate.	Bleed the pumping system before use to deprive system of air.
Ball size reduction below expectation (less than 14mm)	Excessive ball wear rate	None effective cleaning	Periodically replace balls according to manufacturer catalogue.
Ball losses	Ball stuck on strainer Circulatory pump malfunctioning Ball stuck in water box dead spots of low flow pattern	Poor ball distribution at tubes hence tube missed on cleaning.	Strainer modifications, avoid air entrapped in the circuit, fill in dead spots in condenser water box.
Ball blockages	Wrong ball selection, reduced flow rate.	Impeded water flow, increased pressure drops.	Install tube flow monitors; avoid macro foulant to pass through the debris filter at the main cooling water inlet pipe.
Reverse flow	Valve malfunction	Balls fail to reach expected destination in time.	Install new valves

6. Conclusions

The introduction of an online condenser cleaning system at the power station will be financially beneficial in that downtimes due to unexpected and unscheduled shutdown would be reduced during periodical cleaning. Annual expenses due to downtime on condenser cleaning can save the power company an estimated $475 200. However, installation of such a system requires total investment of $5,283 which can comfortably be paid back within a period of 1 year and 2 months. This research was innovative in improving the existing system to meet set objectives in that the magnetic water treatment unit used magnetism to alter the super molecules in water such that the calcium cations precipitated as weak aragonite sludge with reduced ability to stick. This was an advantage in that when a tube was missed by the cleaning balls in some cycles, it would certainly be easier to scrub it in the next cycles hence maintaining a continuously running and uninterrupted power station. Increasing the number of balls per cycle also increased the probabilities that any tube was cleaned after multiple cycles. The system also has the flexibility to reduce ball sizes in order to cover for thermal expansion on the balls when exposed to high temperatures. Recommendation were also made for further research to improve the ball outer surfaces, distribution and monitoring of motions within the tubes.

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